

Limit on sterile neutrino contribution from the Mainz Neutrino Mass Experiment

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Abstract

The recent analysis of the normalization of reactor antineutrino data, the calibration data of solar neutrino experiments using gallium targets, and the results from the neutrino oscillation experiment MiniBooNE suggest the existence of a fourth light neutrino mass state with a mass of $\mathcal{O}(\text{eV})$, which contributes to the electron neutrino with a sizable mixing angle. Since we know from measurements of the width of the Z^0 resonance that there are only three active neutrinos, a fourth neutrino should be sterile (i.e., interact only via gravity). The corresponding fourth neutrino mass state should be visible as an additional kink in β -decay spectra. In this work the phase II data of the Mainz Neutrino Mass Experiment have been analyzed searching for a possible contribution of a fourth light neutrino mass state. No signature of such a fourth mass state has been found and limits on the mass and the mixing of this fourth mass states are derived.

1 Introduction

Experiments with atmospheric, solar, reactor and accelerator neutrinos gave compelling evidence that neutrinos from one flavor state can be detected in another flavor state after some flight distance. This well-established phenomenon *neutrino oscillation* is usually explained by neutrino mixing: Firstly, the three flavor neutrino states ν_e , ν_μ and ν_τ are superpositions of three neutrino mass eigenstates ν_1 , ν_2 and ν_3 connected by a unitary 3×3 mixing matrix U . Secondly, neutrino oscillations require that the three neutrino mass states differ in masses, i.e. at least two neutrino mass states ν_i possess non-zero masses. Neutrino oscillation experiments yielded the three mixing angles θ_{23} ($\sin^2 \theta_{23} = (3.86^{+0.24}_{-0.21}) \cdot 10^{-1}$), θ_{12} ($\sin^2 \theta_{12} = (3.07^{+0.18}_{-0.16}) \cdot 10^{-1}$) and recently θ_{13} ($\sin^2 \theta_{13} = (2.41^{+0.25}_{-0.25}) \cdot 10^{-2}$), as well as the two splittings between squared neutrino masses $\Delta m_{12}^2 = m^2(\nu_2) - m^2(\nu_1) = (7.54^{+0.26}_{-0.22}) \cdot 10^{-5} \text{ eV}^2$ and $|\Delta m_{23}^2| = |m^2(\nu_3) - m^2(\nu_2)| = (2.43^{+0.16}_{-0.10}) \cdot 10^{-3} \text{ eV}^2$ (all values quoted after [1], using conventional units with $c = 1$ and $\hbar = 1$)¹.

Nearly all these oscillation experiments – performed with neutrinos with very different energies, different flavors, different flight distances and with/without matter effects – can be described by three neutrino mass and three neutrino flavor states connected by a unitary 3×3 matrix. Yet, there is an increasing number of hints that this picture is not complete: There is the request for at least one additional scale

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¹The values here are given under the assumption of the normal neutrino mass hierarchy, i.e. $m(\nu_3) > m(\nu_2) > m(\nu_1)$, which slightly differ from the results for the inverted hierarchy $m(\nu_2) > m(\nu_1) > m(\nu_3)$.

of neutrino squared mass splittings $\Delta m_{ij}^2 = \mathcal{O}(\text{eV})$ from the so called *reactor neutrino anomaly* [2], the normalization of gallium solar neutrino experiments [3, 4, 5, 6], and from the accelerator neutrino experiments LSND [7] and MiniBooNE [8]. Although cosmology gave hints that the number of neutrino degrees of freedom is rather four than three, introducing an eV mass scale is not trivial [9]. Since we know from the LEP studies of the Z^0 pole that the number of active neutrinos coupling to the W^\pm and the Z^0 bosons is 2.9840 ± 0.0082 [10] the fourth neutrino has to be sterile. By neutrino mixing the fourth neutrino state will become visible in neutrino oscillation and direct neutrino mass experiments [11]. The existence of sterile neutrinos is quite natural, because most theories describing non-zero neutrino masses exhibit right-handed and therefore sterile neutrinos. What is less natural is the eV-scale discussed here. A summary of the physics and searches for sterile neutrinos can be found in a recent white paper [12].

Our paper is organized as follows: In section 2 we discuss the influence of a fourth sterile neutrino on the spectrum of an allowed β -decay. The Mainz Neutrino Mass Experiment is described briefly in section 3. In section 4 we present the result of a sterile neutrino search in the phase II data of the Mainz Neutrino Mass Experiment before we give a conclusion and an outlook in section 5.

2 Neutrino mass signature in β -decay

The energy spectrum $\dot{N}(E)$ of the β -electrons of an allowed β -decay is given by [13, 14]:

$$\begin{aligned} \dot{N}(E) = & \frac{G_F^2 \cdot \cos^2 \Theta_C}{2\pi^3} \cdot |M_{\text{nucl}}^2| \cdot F(E, Z') \cdot (E + m) \cdot \sqrt{(E + m)^2 - m^2} \\ & \cdot \sum_{i,j} |U_{ei}^2| \cdot P_j \cdot (E_0 - V_j - E) \cdot \sqrt{(E_0 - V_j - E)^2 - m^2(\nu_i)} \\ & \cdot \Theta(E_0 - V_j - E - m(\nu_i)). \end{aligned} \quad (1)$$

Here E and m denote the kinetic energy and mass of the electron, G_F and Θ_C Fermi's constant and the Cabibbo angle, M_{nucl} the nuclear matrix element of the β -decay, $F(E, Z')$ the Fermi function describing the Coulomb interaction of the outgoing electron with the remaining daughter nucleus of charge Z' , P_j the probabilities to find the daughter ion after the β -decay in an electronic or rotational-vibrational excitation with excitation energy V_j , and E_0 the maximum possible kinetic energy of the β -electron in case of $m(\nu_i) = 0$, which is the Q -value of the decay minus the recoil energy of the daughter [14]. Θ is the Heaviside function.

Assuming a fourth sterile neutrino ν_s (or even a larger number of sterile neutrinos) requires to increase the number of neutrino flavor and mass states as well as the dimensions of the mixing matrix U :

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}. \quad (2)$$

The sum over the neutrino mass states in equation (1) will then run from $i = 1$ to $i = 4$. Now we introduce the following simplification: The three neutrino states ν_1 , ν_2 and ν_3 are assumed to have about the same mass $m(\nu_{\text{light}}) \approx m(\nu_1) \approx m(\nu_2) \approx m(\nu_3)$. This assumption² is supported by the small differences between the squared neutrino masses found in neutrino oscillations (see section 1). We can now sum up the first three terms $|U_{ei}^2|$ in equation(1) and describe it by a single mixing angle ϑ :

$$\sum_{i=1}^3 |U_{ei}^2| =: \cos^2(\vartheta), \quad |U_{e4}^2| =: \sin^2(\vartheta). \quad (3)$$

²We could even allow small differences between the three light neutrino masses $m(\nu_1)$, $m(\nu_2)$, $m(\nu_3)$ and expand the j -th component of the β -spectrum to first order in $m^2(\nu_i)/(E_0 - V_j - E)^2$ [14]. Then we can define the *electron neutrino mass squared* as average over all light mass eigenstates contributing to the electron neutrino: $m^2(\nu_e) := \sum_{i=1}^3 |U_{ei}|^2 m^2(\nu_i)$, which would correspond to the mass of the light neutrino mass state $m^2(\nu_e) \approx m^2(\nu_{\text{light}})$.

Equation (1) then simplifies to

$$\begin{aligned}
\dot{N}(E) = & \frac{G_F^2 \cdot \cos^2 \Theta_C}{2\pi^3} \cdot |M_{\text{nucl}}^2| \cdot F(E, Z') \cdot (E + m) \cdot \sqrt{(E + m)^2 - m^2} \\
& \cdot \sum_j P_j \cdot (E_0 - V_j - E) \\
& \cdot \left(\cos^2(\vartheta) \cdot \sqrt{(E_0 - V_j - E)^2 - m^2(\nu_{\text{light}})} \cdot \Theta(E_0 - V_j - E - m(\nu_{\text{light}})) \right. \\
& \left. + \sin^2(\vartheta) \cdot \sqrt{(E_0 - V_j - E)^2 - m^2(\nu_4)} \cdot \Theta(E_0 - V_j - E - m(\nu_4)) \right). \quad (4)
\end{aligned}$$

From equation (4) it is obvious that the endpoint region of a β -spectrum is the most sensitive region to search for a contribution of a sterile neutrino with a mass $m(\nu_4) = \mathcal{O}(1 \text{ eV})$. Therefore, tritium and ^{187}Re are the β -emitters of choice due to their endpoint energies of $E_0 = 18.57 \text{ keV}$ and $E_0 = 2.47 \text{ keV}$, respectively, which are the two lowest known β -endpoint energies. Figure 1 shows a β -spectrum near its endpoint E_0 for an arbitrarily chosen contribution of a fourth sterile neutrino mass state.

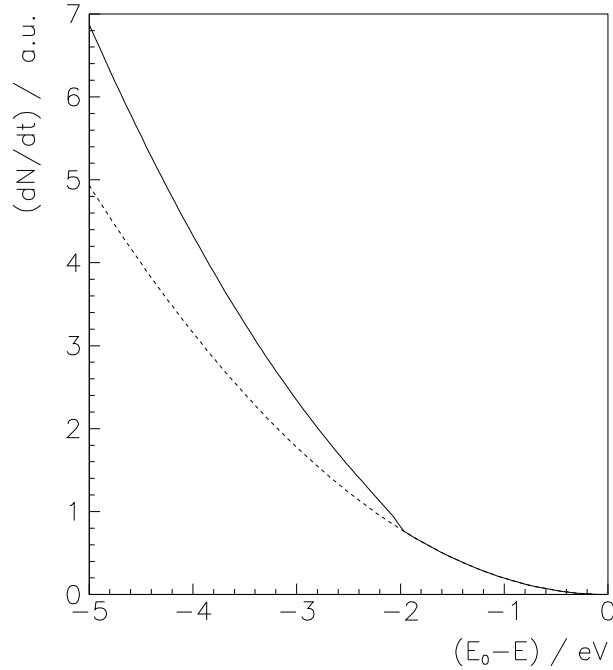


Figure 1: Allowed β -spectrum near the endpoint E_0 with an admixture of a heavy neutrino with $m(\nu_4) = 2 \text{ eV}$, $\sin^2(\vartheta) = 0.3$. The dashed line shows the β -spectrum with the light neutrino state $m(\nu_{\text{light}}) = 0 \text{ eV}$ only.

3 Phase II of the Mainz Neutrino Mass Experiment

The Mainz Neutrino Mass Experiment was investigating the endpoint region of the tritium β -spectrum from 1991 to 2001 to search for a non-zero neutrino mass [15, 16]. In the following we will only describe and discuss the data of the Mainz phase II (1998–2001) after the upgrade which took place from 1995 until 1997.

The Mainz Neutrino Mass Experiment used an integrating electrostatic retardation spectrometer with magnetic guiding and collimating field of MAC-E-Filter type [17]. This spectrometer type combines a large accepted solid angle with a high energy resolution. The retardation potential was created by a system of 27 cylindrical electrodes which were installed within an ultrahigh vacuum vessel of 1 m diameter and 3 m length. The β -spectrum was scanned over the last 200 eV below the endpoint E_0 by setting about 40 different retarding voltages and counting the corresponding number of transmitted β -electrons. To eject stored electrons, which could cause background, from the spectrometer, HF pulses on one of the electrodes were applied for about 3 s every 20 s between the measurements at a constant retarding voltage. A system of 5 superconducting solenoids provided the magnetic guiding field for the β -electrons from the tritium source in the first solenoid through a magnetic chicane through the spectrometer to a silicon detector. The tritium source consisted of a thin film of molecular tritium which was quench-condensed onto a cold graphite substrate and kept at a temperature below 2 K. By laser ellipsometry the film thickness was determined to be typically 150 monolayers. The magnetic chicane eliminated source-correlated background. The low temperature below 2 K avoided the roughening transition of the homogeneously condensed tritium films with time [18]. Figure 2 illustrates the Mainz setup.

In 1998, 1999 and 2001 in total 6 runs of about one month duration each were taken under good and well-controlled experimental conditions. These data were analyzed with regard to the neutrino mass $m(\nu_e)$ [16]. The main systematic uncertainties of the Mainz experiment were the inelastic scattering of β -electrons within the tritium film, the excitation of neighbor molecules due to sudden change of the nuclear charge during β -decay, and the self-charging of the tritium film as a consequence of its radioactivity. As a result of detailed investigations in Mainz [19, 20, 21, 16] – mostly by dedicated experiments – the systematic corrections became much better understood and their uncertainties were reduced significantly. The high-statistics Mainz phase II data (1998–2001) allowed the first determination of the probability of the neighbor excitation, which was found to occur in $(5.0 \pm 1.6 \pm 2.2) \%$ of all β -decays [16], in good agreement with the theoretical expectation [22].

The analysis of the last 70 eV below the endpoint of the phase II data gave no indication for a non-zero

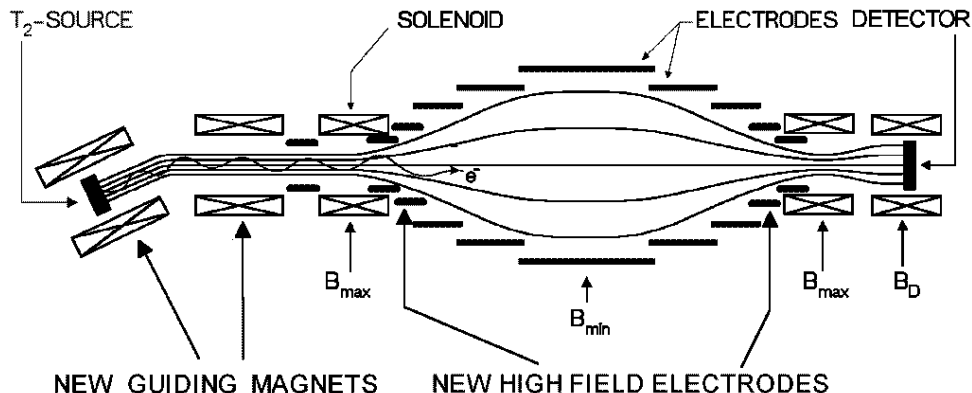


Figure 2: Illustration of the Mainz Neutrino Mass Experiment after its upgrade for *phase II*. The outer diameter of the spectrometer amounted to 1 m, the distance from source to detector was 6 m. See text for details.

neutrino mass (see also figure 3) [16]. The result for the squared neutrino mass,

$$m^2(\nu_e) = (-0.6 \pm 2.2 \pm 2.1) \text{ eV}^2, \quad (5)$$

corresponds – using the Feldman-Cousins method [23] – to an upper limit of

$$m(\nu_e) < 2.3 \text{ eV} \quad (95 \% \text{ C.L.}). \quad (6)$$

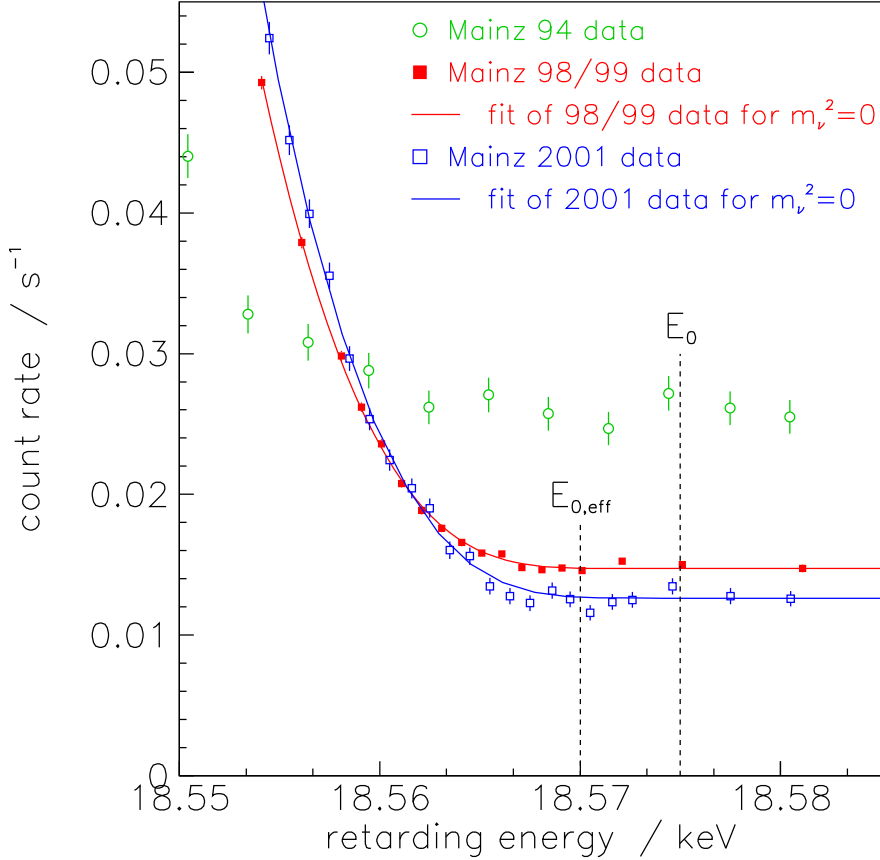


Figure 3: Averaged count rate of the Mainz 1998/1999 data (filled red squares) with fit for $m(\nu_e)=0$ (red line) and of the 2001 data (open blue squares) with fit for $m(\nu_e)=0$ (blue line) in comparison with previous Mainz data from 1994 (open green circles) as a function of the retarding energy near the endpoint E_0 and effective endpoint $E_{0,\text{eff}}$. The latter takes into account the width of the response function of the setup and the mean rotation-vibration excitation energy of the electronic ground state of the $^3\text{HeT}^+$ daughter molecule.

4 Analysis of Mainz phase II data with respect to sterile neutrino contribution

We now analyze the six runs of the Mainz phase II data with regard to a possible contribution of a sterile neutrino. In the former Mainz phase II analysis the following four fit parameters were determined by a fit to the data: the electron neutrino mass squared $m^2(\nu_e)$, the endpoint energy E_0 , the normalizing amplitude a and a constant background rate b .

For our sterile neutrino analysis we assume that the light neutrino mass can be neglected: $m(\nu_{\text{light}}) = m(\nu_e) = 0$ compared to the mass of the heavy sterile neutrino $m(\nu_4)$. This is not only justified by the neutrino mass limit shown in equation (6) but also from a similar limit of the neutrino mass experiment at Troitsk [24] and from even more stringent neutrino mass limits from cosmology (e.g. [25]). To describe the β -spectrum including a fourth sterile neutrino mass state we use equation (4). Hence, we have now five fit parameters instead of the four fit parameters of the previous neutrino mass analysis: the squared mass of the heavy sterile neutrino $m^2(\nu_4)$, its contribution by mixing $\sin^2 \vartheta$, the endpoint energy E_0 , the normalizing amplitude a and a constant background rate b .

In all other respects we do exactly the same as for the Mainz phase II analysis [16]. This includes using the same data sets of the six runs, which comprise the measured count rates as a function of the retarding voltage U , as well as applying the same so-called response function $T'(E, U)$ of the Mainz apparatus. Our fit function $F(U)$ should describe the expected count rate as function of the retarding voltage U of the spectrometer. To obtain this fit function the β -spectrum $\dot{N}(E)$ including a fourth, sterile neutrino (4) is convolved with the response function $T'(E, U)$ of the apparatus and a constant background rate b is added:

$$F(U) = \int \dot{N}(E) \cdot T'(E, U) \, dE + b = \dot{N} \otimes T' + b. \quad (7)$$

The response function $T'(E, U)$ itself is a fivefold convolution of the transmission function T_{spec} of the spectrometer of MAC-E-Filter type, the energy loss function of the β -electrons in the T_2 film f_{loss} [19], the charge-up potential in the film f_{charge} [21], the backscattering function from the graphite (HOPG) substrate f_{back} , and the energy dependence of the detector efficiency f_{det} [16]:

$$T'(E, U) = T_{\text{spec}} \otimes f_{\text{loss}} \otimes f_{\text{charge}} \otimes f_{\text{back}} \otimes f_{\text{det}}. \quad (8)$$

The five functions T_{spec} , f_{loss} , f_{charge} , f_{back} , f_{det} are described in detail in the Mainz phase II analysis paper [16] and we copy the former analysis methods by even applying the same computer programs for these five functions and for $T'(E, U)$.

For calculating the β -spectrum we use the final states distribution from the Mainz phase II analysis [26] including also the excitation of neighboring T_2 molecules during the β -decay and small shifts of higher excited electronic states in solid T_2 with respect to gaseous T_2 as described in the Mainz phase II analysis [16]. Although there are two slightly updated final states distributions [27, 28] the differences are so tiny that we still used the one [26] which has been applied for the Mainz phase II analysis.

Fitting was done by the usual χ^2 minimization method applying the program MINUIT from CERN. Our systematic uncertainties we derived in the same way as for the Mainz phase II analysis: For every parameter p with systematic uncertainty Δp , e.g. the thickness of the T_2 film, we performed the whole fitting three times, with the parameter set to p , to $p - \Delta p$ and to $p + \Delta p$, respectively. The obtained variations in our observable of interest $\sin^2 \vartheta$ for a fixed mass squared of the fourth neutrino mass state $m^2(\nu_4)$ defined the systematic uncertainty to our observable $\pm 1\sigma_{p,\text{sys}}(\sin^2 \vartheta)$ by the parameter p . Since the uncertainty Δp of the parameter p , e.g. the uncertainty of the film thickness, usually differs among the six data sets we calculated the correct average by minimizing the χ^2 for all six data sets together, as described in the Mainz phase II analysis [16].

We do not want to repeat here the detailed explanation of all the systematic uncertainties because we adopt them from the Mainz phase II analysis [16]. Instead we just list the systematic uncertainties taken into account: The shift of the energy of excited first and second electronic final state groups in

Table 1: List of systematic corrections and their relative uncertainties as from reference [16].

correction	relative uncertainty
shift of excited electronic final states	1
inelastic cross section	0.054
film thickness	0.03
film coverage by condensing H ₂	1
neighbor excitation	0.28
self-charging of the tritium film	0.2
energy dependence of detector efficiency & backscattering	0.5

solid T₂ w.r.t. gaseous T₂, the uncertainties of the inelastic cross section and of the thickness of the T₂ films, of the coverage of the T₂ films by condensing H₂ gas with time, of the probability to excite neighboring T₂ molecules by the β -decay, of the correction for the self-charging which the electrically insulating T₂ film undergoes as it loses β -electrons continuously, of the backscattering of β -electrons in the HOPG substrate, and of the energy-dependence of the detector efficiency. The relative uncertainties of these corrections are listed in table 1.

The final result on the light neutrino mass squared in equation (5) was obtained by fitting the last 70 eV of the β -spectrum. In the sterile neutrino analysis we also used the last 70 eV of the measured β -spectra

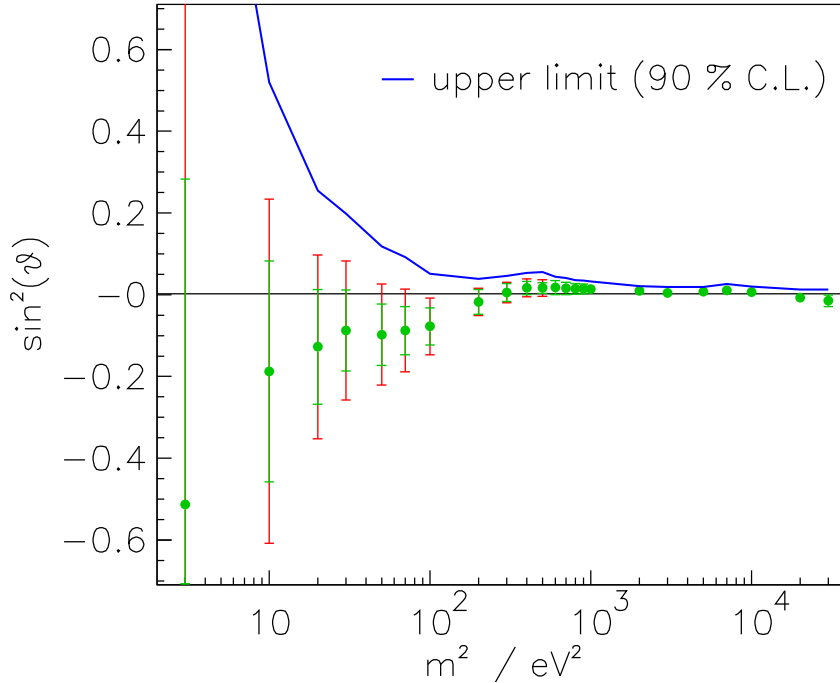


Figure 4: Fit results on the contribution $\sin^2 \vartheta$ of a fourth neutrino mass state ν_4 from the analysis of the Mainz phase II data as function of the squared mass $m^2(\nu_4)$. The inner (green) error bars correspond to the statistical, the outer (red) to the total uncertainty. The blue line above the points with error bars gives the upper limit according to the Feldman-Cousins method [23] with 90 % C.L.

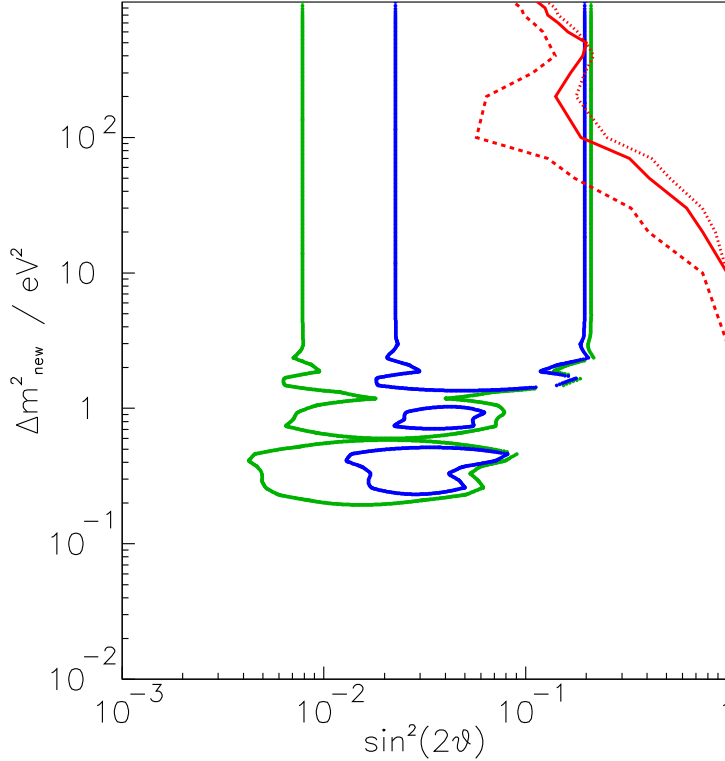


Figure 5: Favored region of the so-called *reactor neutrino anomaly* at 90 % C.L. in blue and at 95 % C.L. in green as function of the mixing of the fourth neutrino mass state to the electron neutrino $\sin^2(2\vartheta)$ and the squared mass difference of the fourth neutrino mass state to the light neutrino mass states Δm_{new}^2 (courtesy of T. Lasserre). The red curves represent the limits from this analysis at 68 % C.L. (dashed), 90 % C.L. (solid) and 95 % C.L. (dotted), respectively. The parameter regions right of and above the curves are excluded. Here we neglect a possible non-zero value of the light neutrino mass states and show the limits for $m^2(\nu_4) = \Delta m_{\text{new}}^2$.

of the six runs for heavy neutrino masses $m^2(\nu_4) \leq 1000 \text{ eV}^2$; for larger $m(\nu_4)$ we extended the fit range proportional to $m(\nu_4)$ up to fitting the last 200 eV of the measured β -spectra for $m^2(\nu_4) = 20000 \text{ eV}^2$.

Figure 4 shows the fit results for the contribution $\sin^2 \vartheta$ as a function of the squared mass of the fourth neutrino mass state $m^2(\nu_4)$. For small $m^2(\nu_4)$ the sensitivity decreases due to lack of statistics. For large squared masses $m^2(\nu_4)$ the variation in sensitivity is caused by the fact that the measurement points of the Mainz phase II runs are not equally distributed along the energy scale. No indication of a contribution of a fourth neutrino mass state is found, the contribution $\sin^2 \vartheta$ is compatible with zero for all squared masses $m^2(\nu_4)$ of the fourth neutrino mass state under investigation. The line above the fit points gives the corresponding upper limit according to the Feldman-Cousins method at 90 % C.L. [23].

Figure 5 shows the parameter space favored in order to explain the reactor neutrino anomaly by the mixing of a fourth neutrino mass state [2] together with the limit on this fourth neutrino mass state from our analysis. The phase II data of the Mainz Neutrino Mass Experiment allow to exclude a small fraction of the favored parameter space at large Δm^2 .

5 Conclusion and outlook

Our re-analysis of the phase II data of the Mainz Neutrino Mass Experiment with regard to a potential contribution of a fourth neutrino mass state to the electron neutrino does not give any hint for the existence of such a state. The contribution $\sin^2 \vartheta$ is compatible with zero for all squared masses of the fourth neutrino mass state under investigation ($3 \text{ eV}^2 \leq m^2(\nu_4) \leq 30,000 \text{ eV}^2$). The Mainz data constrain a small fraction of the parameter space for such a fourth neutrino mass state favored by the attempt to explain the reactor neutrino anomaly and other indications.

The Karlsruhe Tritium Neutrino experiment KATRIN [29] will investigate the endpoint region of the tritium β -decay with much higher statistics, better energy resolution and much smaller systematic uncertainties. The KATRIN experiment will reach a factor 10 higher sensitivity on the electron neutrino mass of 200 meV compared to the sensitivity of the Mainz Neutrino Mass Experiment as reported in equation (6). The data from the KATRIN experiment will also allow to investigate the potential contribution of a fourth neutrino mass state to the electron neutrino with a sensitivity [30, 31, 32] covering the whole favored region of the *reactor neutrino anomaly*.

A fourth neutrino mass state with a mass of a few keV acting as Warm Dark Matter is another possibility, which derives its motivation from recent efforts of explaining the structure of the universe at galactic and super-galactic scales (*missing satellite galaxy problem*) [33]. Such a neutrino might also be investigated by β -decay studies [34].

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